"Zhurnal Tekhnicheskoy Fiziki" No. 6, 1948

CORRESPONDING STATES OF METALS

M. A. Zaykov

abstract

In developing the theory of corresponding states of metals, the author found it necessary to investigate the mechanical (physical) properties of metals in so-called "relative or reduced coordinates" that permit one to synthesize or bring together the properties of all metals into one curve, expressed by one equation. The equation is verified by experiments of the authors and others.

1. The Object and Theory of the Problem

The superficial similarity of curves describing the temperature dependence of the characteristics of various metals has for a long time (Figure 1) provoked attempts to find a general principle covering this and to reduce all curves into one, expressed by one equation, as was done by Van der Waal for gases in the form of a reduced equation of state. The notion of extending the theory of corresponding states to solids was first put forth by Abogadro/1/. Ludwik/2/, in developing this idea, suggested introducing the concept of corresponding or homologous temperatures ($\frac{T}{T_{pl}}$). In verification of this, he performed a great many tests, mainly with non-ferrous metals. Figure 2 represents the maximum strength of certain metals at homologous temperatures. It can be seen in Figure 2 that in comparison with Figure 1 the curves shifted, but there is no complete conformity.

Failures in solving this important problem are due to the fact that one serious factor was omitted; namely, the

CONFIDENTIAL

allotropy of the metals, which considerably distorts the curve describing the temperature dependence of the mechanical properties of metals. On the basis of very abundant material in the literature, it can be concluded that during phase transformations a fully comprehensible intermittent variation in properties takes place, eliminating the distortions not allowed for by homologous coordinates; in regions of separate modification, however, the curves are actually of the same kind and do not generally distinguish themselves for different metals.

On the basis of the latter, it appears correct to extend Ludwik's principle of homologous temperature only to single modifications and to apply in full Van Der Waal's theory of corresponding states; that is, to introduce the concept of not only corresponding temperatures, but also the corresponding mechanical characteristics.

It was earlier[3] established that the relation of mechanical characteristics to temperature is expressed by an exponential equation

$$\sigma = \sigma_0 \cdot e^{-mT} \qquad (1)$$

or

$$\ln \sigma = \ln \sigma_0 - mT \qquad (1a)$$

Here sigma is the sought-for mechanical characteristic (for example σ_b, σ_x, σ_s, etc.) at the temperature T expressed on the absolute scale; σ_0 is the constant of the equation, of the same dimension as σ, obtained by extrapolating the curve to o°K; m is the temperature coefficient :

$$m = \frac{d}{dT}(\ln \sigma) = \frac{\ln \sigma - \ln \sigma K}{T_H - T_K} \qquad (2)$$

CONFIDENTIAL

It is more correct to extend the extrapolated curve to the origin of the temperature interval for the given phase; then the equation will take the form

$$\ln \sigma = \ln \sigma_{origin} - m(T - T_{origin}) \qquad (1b)$$

For conversion to the corresponding state we change Ludwik's reduced (homologous) ratio T/T_{pl} to

$$\frac{T - T_H}{T_K - T_H} = \tau \qquad (3a)$$

Here $T_k - T_H$ is the temperature interval in units of $^\circ C$; $T - T_H$ is the magnitude of heating of the solid, with T_H as the zero position. Extending this principle also to the axis of the mechanical characteristics, we shall obtain

$$\frac{\sigma - \sigma_K}{\sigma_H - \sigma_K} = \delta \qquad (3b)$$

and

$$\frac{\ln \sigma - \ln \sigma_K}{\ln \sigma_H - \ln \sigma_K} = \frac{\lg \sigma - \lg \sigma_K}{\lg \sigma_H - \lg \sigma_K} = \lambda \qquad (3c)$$

After jointly solving (1), (2), (3a), and (3b), and making simple transpositions, we obtain the reduced equation of the corresponding states of metals

$$\lambda + \tau = 1 \qquad (4)$$

or

$$\frac{\sigma}{\sigma_H} = \left(\frac{\sigma_K}{\sigma_H}\right)^{\tau} \qquad (5)$$

CONFIDENTIAL

These equations are remarkable in that they appear to be common to all solids (within the limits of single modifications or temperature ranges) in the hard state; it is evident also that any conclusions evolving from them should apply to all solids.

For practical application, equation (5) can be simplified by logarithms and joint solution with (4)

$$\lg \sigma = \lg \sigma_H - \lg \frac{\sigma_H}{\sigma_K} \tau \qquad (5a)$$

or

$$\lg \sigma = \tau \lg \sigma_K + \lambda \lg \sigma_H \qquad (5b)$$

2. The Experimental Portion

In order to prove and verify equations (4) and (5) tests were performed by breaking down various carbon steels in the regions of single modifications. Carbon steels of carbon content 0.12 to 1.19% were used in the investigation. The tests were conducted at various speeds from 0.002 mm/sec to 50 mm/sec; the temperature range was from 20 to 1300° C. The method of conducting the tests is described in detail in /3/ and /4/; therefore we shall not take it up here. We have also used material from the literature to illustrate the common character of conclusions drawn.

The tested material is systematically broken up into stages.

Stage 1. Low-Melting Metals

Table 1 (~~Graphs~~ Columns t^o and σ Bexper) shows Ludwik's data./2/

Low-melting metals are used for analysis; namely, tin, lead, zinc, magnesium produce the greatest difference in Ludwik's homologous coordinates and are completely unrelated when in ordinary coordinates (Figure 1). The tangent of slop m and the temporary resistance at the temperature of fusion are determined by equations (1) and (2). Table 1 shows the data calculated according to the relations (5), (5a), and (5b).

Table 2 shows the results of converting tested data for lead (from Table 1) according to the concluded equation of the corresponding conditions (4) and (3a), (3b), (3c).

Table 1 and 2 illustrate the accuracy of equations (4) and (5) and the agreement of the various calculated values with the experimental values.

Stage II. Polymorphous Metals.

Experimental data for research was taken for metals most representative of this group. The author's tests encompassed almost the whole range of applicable steel from 0.12 C to 1.19% C and were conducted for alpha- and gamma-modification.

Table 3 shows experimental data relating to the extent of stability of soft steel in a temperature range from -230 to + 1300°C. Hatfield's data /5/ was used for negative temperatures.

It can be seen from Tables 2 and 3 that the value of ( ) obtained experimentally satisfactorily agrees with the theoretical calculated values (equation 4.

CONFIDENTIAL

A similar agreement of experimental values of strength with the calculated values was obtained for steel 2 for a variable rate of deformation ranging from 0.002 to 50 mm/sec and for various carbon steels of carbon content 0.12 to 1.2% for a rate of deformation v = 0.01 mm/sec (Figures 3 and 4).

Table 4 represents the experimental data of Vratskiy and Frantsevich /6/ relating to the strength of chromium steel EKh2 at high temperatures and for a rate of deformation v ≅ 2.5 mm/sec. A calculation is also given of this data according to formulas of corresponding conditions (4) and (3a), (3b), (3c); for comparison, maximum strength is calculated according to formula (5a).

It is evident from the tables that the alloyed steels are also satisfied by equations (4) and (5).

The graphs of Figures 3 and 4 are drawn in accordance with the table 1-4 to illustrate the agreement of the curves, which widely diverge in Figures 1 and 2.

Stage III. Various Mechanical Characteristics.

As an analysis of experimental material showed, the most diverse characteristics satisfy equations (4) and (5).

Tables 5a, 5b, and 5c show a comparison of the various mechanical characteristics for copper, experimental and calculated according to equation (5). /7, 8, 9, 10, 11/ They show: the maximum strength, true stress at the moment of fracture and at the moment of 'neck' formation, yield point, and specific pressure during sag, pressing through the container, lamination and cutting in a planing machine

CONFIDENTIAL

according to the data of various authors; temperatures from -193 to + 1000°C and rates of deformation ranging from 0.01 mm/sec to 20 mm/sec are included. It is evident from the Tables that the agreement of calculated and experimental values for all these characteristics is completely satisfactory and consequently they all vary with temperature in accordance with equations (1) and (4); that is, with the exponential equation given.

The Table further shows that the point corresponding to the temperature of recrystallization corresponds to the radical break in the intensity of variation in these properties and should be considered as a point of allotropic conversion for any solution of such a problem.

It is interesting to note further that equations (4) and (5) are also adequately satisfied by the calculations, made with the experimental data on the deformation of monocrystals and complex technical alloys, and also by such mechanical characteristics as: accumulating stress, the modulus of elasticity, hardness by Brinell and Ludwik tests at various stages of soaking, specific pressure during heated cutting with saw, shears, etc.

CONCLUSIONS

1. Experiments were performed with carbon steel, of carbon content ranging from 0.12 to 1.19% for temperatures ranging from 20 to 1300° and deformation rates from 0.002 to 50 mm/sec.
2. A similarity of variations in properties was shown for

CONFIDENTIAL

according to the data of various authors; temperatures from -193 to + 1000°C and rates of deformation ranging from 0.01 mm/sec to 20 mm/sec are included. It is evident from the Tables that the agreement of calculated and experimental values for all these characteristics is completely satisfactory and consequently they all vary with temperature in accordance with equations (1) and (4); that is, with the exponential equation given.

The Table further shows that the point corresponding to the temperature of recrystallization corresponds to the radical break in the intensity of variation in these properties and should be considered as a point of allotropic conversion for any solution of such a problem.

It is interesting to note further that equations (4) and (5) are also adequately satisfied by the calculations, made with the experimental data on the deformation of monocrystals and complex technical alloys, and also by such mechanical characteristics as: accumulating stress, the modulus of elasticity, hardness by Brinell and Ludwik tests at various stages of soaking, specific pressure during heated cutting with saw, shears, etc.

CONCLUSIONS

1. Experiments were performed with carbon steel, of carbon content ranging from 0.12 to 1.19% for temperatures ranging from 20 to 1300° and deformation rates from 0.002 to 50 mm/sec.
2. A similarity of variations in properties was shown for

CONFIDENTIAL

separate modifications and temperature ranges from -230° to $3235^{\circ}C$ and also for mono- and polycrystals.

3. A similarity was shown in the temperature variation of such mechanical characteristics as: maximum stability (temporary resistance), actual resistance to fracture, modulus of elasticity, yield point, Brinell hardness, and also specific pressure during sag, pressing, lamination, cutting by saws, metal-cutting machines, etc.

4. It was further shown that these variations should be considered and compared not in any random temperature range, but in ranges of separate modifications, during which the point corresponding to the beginning of recrystallization produces a break in the intensity of variation in properties and which should be considered the point of allotropic conversion in such problems.

5. It was suggested ~~that~~ Ludwik's principle of homologous temperatures *INSERT but also corresponding mechanical characteristics.

6. There were brought out reduced equations of corresponding state and calculated formulas, producing the possibility of finding intermediate values along two points. All formulas were verified by the experimental data of the author and other researchers.

INSERT

*be extended only to separate modifications, and that Van Der Waal's theory of corresponding states should be fully applied to solids; that is, one should introduce a concent of not only correspondint temperatures,

CONFIDENTIAL

CITED LITERATURE

/1/ I. '. Frantsevich. Deformations of Steel. 23, 1933.

/2/ P. Ludwik. VDI. 59,657, 1915.

/3/ M. A. Zaykov. The Strength of Carbon Steels at High Temperatures, 1946

/4/ M. A. Zaykov. The Influence of the Rate of Deformation upon the Temporal Resistance of Steel at High Temperatures, 1946.

/5/ Hatfield. Steel and Iron (in German). 45, 1397, 1923.

/6/ M. Vratskiy and J. Frantsevich. Steel 4-5, 52, 1935.

/7/ A. Krupkovskiy. Rev. d. met. 28, 529, 1931.

/8/ P. Goerens. Krupp. Monatsch. II, 25, 1927.

/9/ S. I. Gubkin. Theory of Flow of Metallic Substances. 24, 51, 113, 1935

/10/ K. Savitskiy. See V. D. Kuznetsov. The Physics of Solids, III, 213, 1944.

/11/ S. Rinkevich and Ya. Ber. Journal of Metals. 10, 50, 1929

Siberian Metallic Institute

Received by the Editor 10 Oct 1947.

from "Zhurnal Tekhnicheskoy Fiziki" No 6, 1948

FIGURES AND TABLES

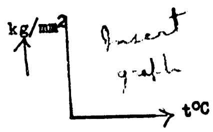
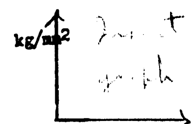


Figure 1. The Temperature Dependence of the Tensile Strength for Certain Metals in Ordinary Coordinates, $\sigma_b = \Phi(t)$.

1-Sn 2-Pb 3-Zn 4-Al
5-Mg 6-Cu 7-Steel 8-Ni
9-U12 10-Ekh2.

P. 847



"e" is a subscript

Figure 2. The Tensile Strength for Certain Metals at Homologous (Reduced) Temperatures. $\sigma_b = \Phi\left(\frac{T}{T_e}\right)$

P. 847

TABLE I Comparison of Experimental and Calculated Data with Respect to the Temporal Resistance of Easily Fused Metals

Lead		Tin	Zinc	Magnesium
a experimental	b calculated	etc		
		Insert figures		

Keys → a, b

P. 850

TABLE II Corresponding Properties of Lead

			σ_B experimental
Insert figures			

etc

P. 851

TABLE III Corresponding Properties (Tensil Strength) of Hard Steel in Various Temperature Intervals, v = 1 mm/sec

			σ_B kg/mm^2
Insert figures			

I Region to 0°C
II Region of alpha-modification
III Region of gamma-modification

P. 852

P. 852

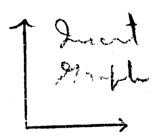


Figure 3. Tensile Strength of Certain Metals in Corresponding Coordinates.
$\sigma_b = \Phi\left(\frac{T-T}{T-T}\right)$

P. 852

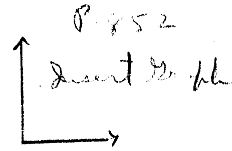


Figure 4. Corresponding States of Metals $\lg \sigma_b = \Phi(T-T)$

8 - Steel 2
9 - Steel 4
10 - U8
11 - Ekh2.

CONFIDENTIAL

Cont'd

TABLE IV. Corresponding Properties of Chrome Steel EKh2 (Tensile Strength) and Comparison of Experimental Quantities with Calculated Quantities

		σ_b (experimental)					σ_b (calculated)
		Insert figures					

P. 853

TABLE 5a. Comparison of Calculated and Experimental Data with Respect to Yield Strength and Tensile Strength of Copper

Yield Strength σ_s kg/mm^2	σ_b kg/mm^2	σ_b kg/mm^2
v = 5 mm/sec E = 0.05	T < $T_{recrystall.}$	T > $T_{recrystallization}$

subscript

subscript

Keys

$T^\circ C$	a. experimental data [9]	b. calculated data	etc.
	Insert figures		

P. 85

TABLE 5b. Comparison of Calculated and Experimental Date for True Stress for Various Coppers

True Stress at the Moment of 'Neck' formation neck kg/mm^2	True Stress at the Moment of Fracture σ_z kg/mm^2	
T > $T_{recrystall.}$	T < $T_{recrystall.}$	T > $T_{recryst}$

subscript

subscript

subscript

$T^\circ C$	a. Experimental Data	b. Calculated Data	etc
	Insert figures		

P. 853

TABLE 5c. Comparison of Calculated and Experimental Data with Respect to Specific Pressure for Various Forms of Deformation of Copper.

Specific Pressure P kg/mm^2				
for Compression 3 = 1.66 mm/sec		for pressing	for rolling	for cutting on a planing machine v = 8 mm/sec
exper. data a.	calculated data b.			

Insert figures

P. 854

CONFIDENTIAL

-11-

— END —

TABLE IV. Corresponding Properties of Chrome Steel EKh2 (Tensile Strength) and Comparison of Experimental Quantities with Calculated Quantities

		σ_b (experimental)					σ_b (calculated)
		Insert figures					

P. 853

TABLE 5a. Comparison of Calculated and Experimental Data with Respect to Yield Strength and Tensile Strength of Copper

Yield Strength σ_p kg/mm²			σ_b kg/mm²	σ_b kg/mm²
v = 5 mm/sec E = 0.05			T < Trecrystall. subscript	T > Trecrystallization subscript
T°C	a. experi- mental data [9]	b. cal- cul- ated data	etc.	
	Insert figures			

Keys

P. 8

TABLE 5b. Comparison of Calculated and Experimental Date for True Stress for Various Coppers

True Stress at the Moment of 'Neck' formation neck kg/mm²			True Stress at the Moment of Fracture σ_z kg/mm²	
T > Trecrystall. subscript			T < Trecrystall. subscript	T > Trecryst subscript
T°C	a. Experimental Data	b. Calculated Data	etc	
	Insert	Figures		

P. 853

TABLE 5c. Comparison of Calculated and Experimental Data with Respect to Specific Pressure for Various Forms of Deformation of Copper.

Specific Pressure P kg/mm²				
for Compression 3 = 1.66 mm/sec		for pressing	for rolling	for cutting on a planing machine v = 8 mm/sec
exper. data a.	calculated data b.			

Insert Figures

P. 859

CONFIDENTIAL

— END —

50X1-HUM

Page Denied